DEVELOPMENT OF IMPROVED MAGNITUDE MEASURES FOR THE INTERNATIONAL DATA CENTRE

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ABSTRACT

Many of the most important issues in nuclear test monitoring at the International Data Centre (IDC), such as event screening, depend critically on the details of the definitions of the various magnitude measures to be employed by the IDC and their relations to the classical National Earthquake Information Center, International Seismological Centre, and Air Force Technical Application Center magnitude measures, which have historically been used to assess seismic verification capability. Therefore, it is important that these IDC magnitude measures be well understood and carefully calibrated. During the past year, we have been continuing to refine the IDC m_b and M_S magnitude measures and have initiated an effort to implement an automated L_g-based magnitude measure for application to small, continental seismic events. The effort on m_b has been directed toward incorporation of PKP observations into the generalized m_b determination. A GLM statistical analysis has now been performed on the large sample of PKP amplitude measurements determined from the PIDC IMS station observations to obtain new distance corrections applicable over the PKP distance range. The resulting distance corrections have been compared both with those currently being employed at the IDC and with those previously derived by Lilwall (1987) and some significant differences have been noted. Moreover, the estimated uncertainties in these derived epicentral distance correction factors for PKP have been found to be comparable to or smaller than those previously estimated for the normal teleseismic P distance range. Thus it appears that incorporation of PKP data, will significantly reduce the nominal uncertainties in the network-averaged generalized m_b values for at least some events. Current effort on this task is directed toward the evaluation of the applicability of the previously derived teleseismic P-wave station corrections to PKP observations at those same stations. With regard to the L_g magnitude measure, our goal is to identify an L_g magnitude measure applicable to observations from IMS stations at regional distances which is consistent with the traditional regional magnitude measure, $m_b(L_g)$, and which will be useful for characterizing the sizes of small events observed by the IDC. The L_g magnitude scheme, which we are developing, uses signal measurements in the L_g group velocity window (2.8 km/sec $\leq v \leq$ 3.7 km/sec) from broad-band vertical-component records which have been band-pass filtered in a variety of frequency bands (including a band centered at 1 Hz). We are making several peak and RMS amplitude measures from the L_g window and seeking to identify a stable measurement which is consistent with the traditional L_g magnitude. This effort also requires determination of an appropriate relationship to characterize L_g attenuation in the region surrounding the IMS stations for which the measurements are obtained. For some IMS stations the L_g observations themselves may permit attenuation estimates, but at other stations alternative approaches may be required. We are currently analyzing the observations at selected IMS stations with fairly large samples of L_g detections (e.g. CMAR) to assess consistency between this direct approach and more inferential approaches utilizing L_g attenuation models. Our preliminary results suggest that the L_g attenuation actually observed from regional events surrounding CMAR agrees quite well with models previously derived for this region.

OBJECTIVE

The IDC has the responsibility to characterize and measure seismic sources detected by the global network of stations of the IMS used to monitor the CTBT. The objective of this research program has been to expand and improve the magnitude measurement procedures used to characterize seismic sources at the IDC. We have been seeking to ensure that the magnitudes reported by the IDC are consistent with the definitions of seismic magnitudes and with previous magnitude measures and that they are free of regional biases and biases associated with measurement procedures. We have also been attempting to evaluate new magnitude measures which can help extract as much information as possible about the seismic sources in an automated processing environment.

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RESEARCH ACCOMPLISHED

Work on this project has been directed at three distinct seismic magnitude measures: (1) generalized m_b, (2) surface wave magnitude, M_S, and (3) a regional magnitude measure based on Lg. Significant accomplishments have been made during the past year toward developing and refining each of these magnitude measures for use at the IDC.

Generalized m_b – During this past year the effort to revise the IDC m_b estimation procedure has been extended to allow for the incorporation of PKP data. As in our previous analysis (Murphy et al., 1999), a sample of single station m_b observations from some 25,000 REB events was analyzed using a General Linear Model (GLM) in which the single station values, $m_b(i,j,k)$, are represented as a linear combination of the form:

$$m_b(i,j,k) = m(i) + sta(j) + db(k) + e(i,j,k) \qquad (1)$$

where

$m(i)$ = event magnitude

$sta(j)$ = station correction

$db(k)$ = correction to the current PIDC specified dependence on epicentral distance

$e(i,j,k)$ = error term

The system of equations (1) is solved using the Expectation Maximization Algorithm to minimize the residual error, subject to the constraints:

$$\sum_j sta(j) = 0$$

$$\sum_k db(k) = 0 \qquad \text{for } 23^o < D < 92^o \qquad (2)$$

The constraints (2) are employed to retain the average absolute levels of the event magnitudes for comparison purposes. That is, since the absolute levels of the single station magnitudes are set by arbitrary convention, any constant value could be added to all the single station magnitudes without affecting the error term in (1) in any way and, therefore, it is necessary to constrain the absolute levels of the correction terms for comparison purposes.

The final distance corrections determined from the GLM analysis of the subset of shallow focus ($h < 50$ km) events are shown in Figure 1, where they are compared with those currently employed at the PIDC and with those derived by Lilwall (1987) in his analysis of ISC m_b data. As was noted previously, the smoothed GLM estimates of the corrections for epicentral distance are very similar to those employed by the PIDC (i.e Veith/Clawson), and to those estimated by Lilwall, between about 30 and 90 degrees. However, at distances greater than about 95 degrees, the GLM corrections begin to diverge from the other two sets of proposed corrections. Thus, the GLM corrections between about 110 and 140 degrees are consistently lower than those proposed by Lilwall by as much as 0.3 magnitude units, while both the GLM and Lilwall corrections exhibit significantly narrower troughs at the PKP focal point at around 145 degrees than does that associated with the current PIDC correction curve. Therefore, we propose to replace the current PIDC correction curve between 92 and 180 degrees with the smoothed GLM estimate shown in Figure 1.

In order to specify an optimum algorithm for combining single station m_b observations at all distances and obtain a generalized m_b value, it is necessary to first examine the uncertainties in the derived epicentral distance corrections as a function of distance. For this reason, the standard errors of estimate associated with the GLM shallow focus distance correction estimates of Figure 1 are displayed as a function of epicentral distance as a solid line in Figure 2. It can be seen from this figure that, somewhat surprisingly, with the exception of the P diffraction region around 100 degrees, the uncertainties in the distance corrections in the PKP range are quite comparable to those in the normal teleseismic P range between 25 and 95 degrees. Therefore, with the exception of the narrow range between 92 and 103 degrees, we have constrained the standard error of estimate to the average teleseismic P constant value of 0.28 between 23 and 180 degrees, and smoothed the GLM estimates between 92 and 103 degrees to obtain the final teleseismic epicentral distance dependence of the uncertainty represented by the dashed line in Figure 2.

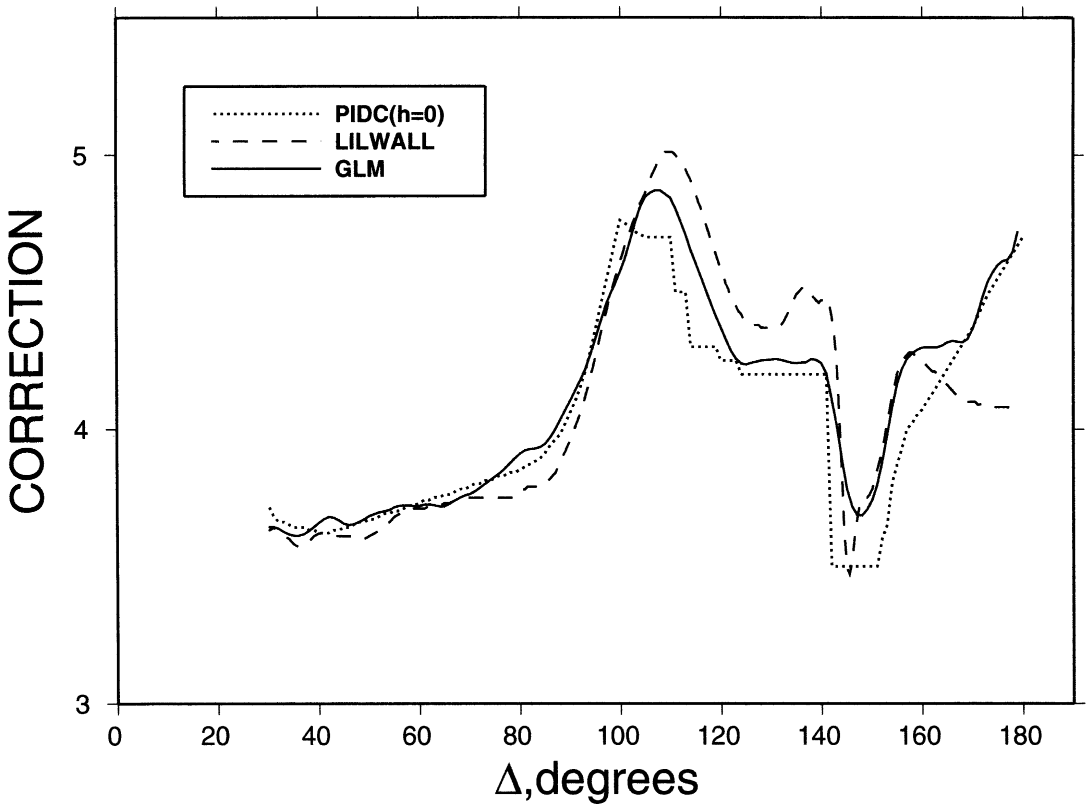


Figure 1. Distance corrections determined from GLM analysis compared to those currently employed at the PIDC and to those derived by Lilwall (1987) in his analysis of ISC data.

The applicability of the m_b station correction factors determined from the previous GLM analysis of the sample of teleseismic P wave data to the PKP observations has also been assessed by comparing these station corrections with the average PKP residuals as a function of distance over the range 100 to 180 degrees. As in our previous analysis of regional P wave data, it has been found that these teleseismic P wave correction factors appear to be generally applicable to the PKP data and produce a significant reduction in variance about the resulting network-averaged m_b values. This fact is illustrated in Figure 3, which shows a comparison of the observed reductions in the standard errors of estimate obtained by applying the station corrections to all the single station P wave data in the distance range from 25 to 180 degrees (left) with those obtained previously for the distance range from 25 to 100 degrees (right). It can be seen that the application of these station correction factors produces comparable reductions in the average standard error of estimate in both cases, corresponding to highly significant reductions of more than 40% in the variance about the resulting network-averaged m_b values. Thus, the station correction factors derived from the teleseismic P wave data appear to be generally applicable over the entire investigated epicentral distance range extending from 2 to 180 degrees. These results are currently being extended to encompass other focal depth ranges of interest.

Regional L_g Magnitude – Although teleseismic magnitude measures are useful for characterizing many of the events observed at the PIDC over the years, it is generally recognized that such magnitudes are not satisfactory for measuring many small events, which may have detected signals at only a few IMS stations. Such events are probably best characterized by observations at regional stations where their signals are strong. During the past year we initiated an effort under this project to identify a regional magnitude measure for use at the IDC. The PIDC has acknowledged the need for regional magnitudes for measuring the size of small events and initially proposed a non-traditional M_L magnitude measure, based on P and P_n observations for stations within 20 degrees of shallow events, to characterize event size. However, this M_L measure has received criticism because it did not correlate very well with teleseismic m_b magnitude measurements. Furthermore, most seismologists prefer a more traditional magnitude scale based on L_g signal amplitude levels measured at regional seismic stations (e.g. $m_b(L_g)$) and taking into account region-dependent attenuation for characterizing the size of small events.

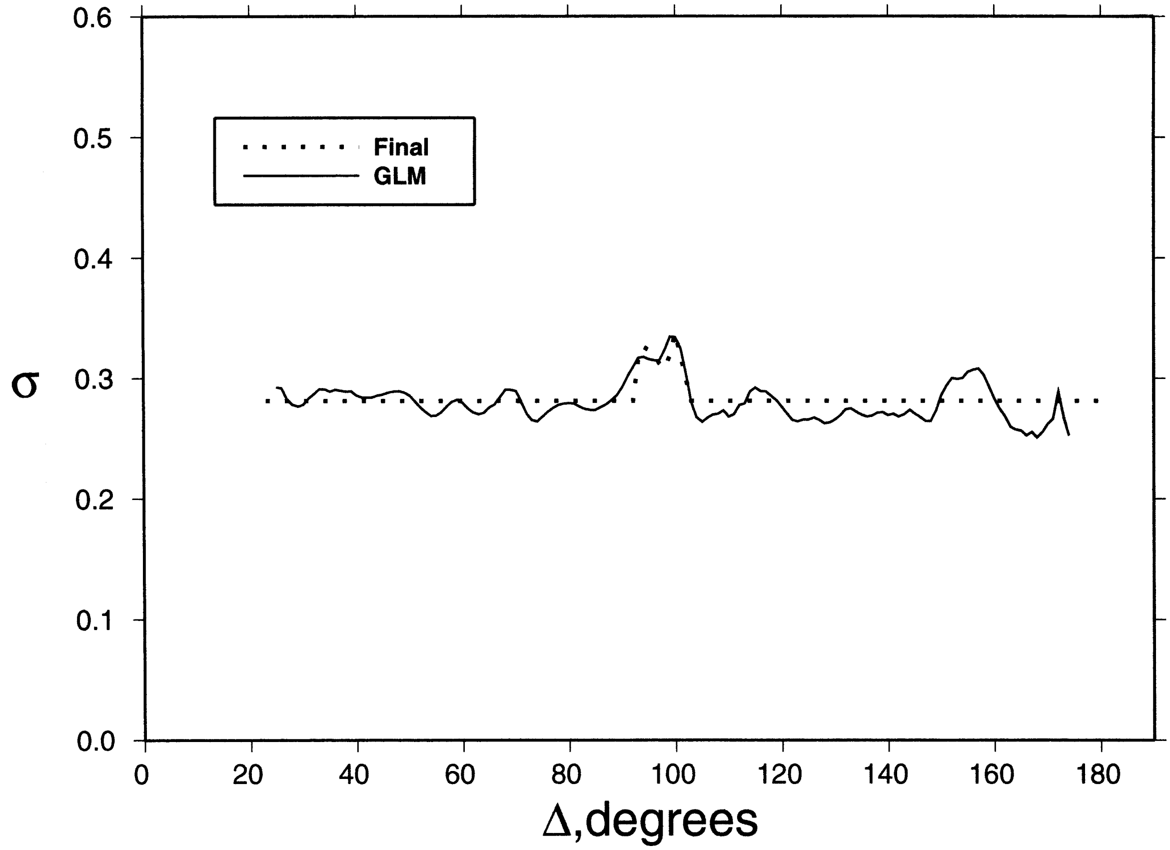


Figure 2. Standard errors of estimate associated with the GLM shallow focus distance correction estimates of Figure 1 compared to our final, smoothed estimate of the uncertainty.

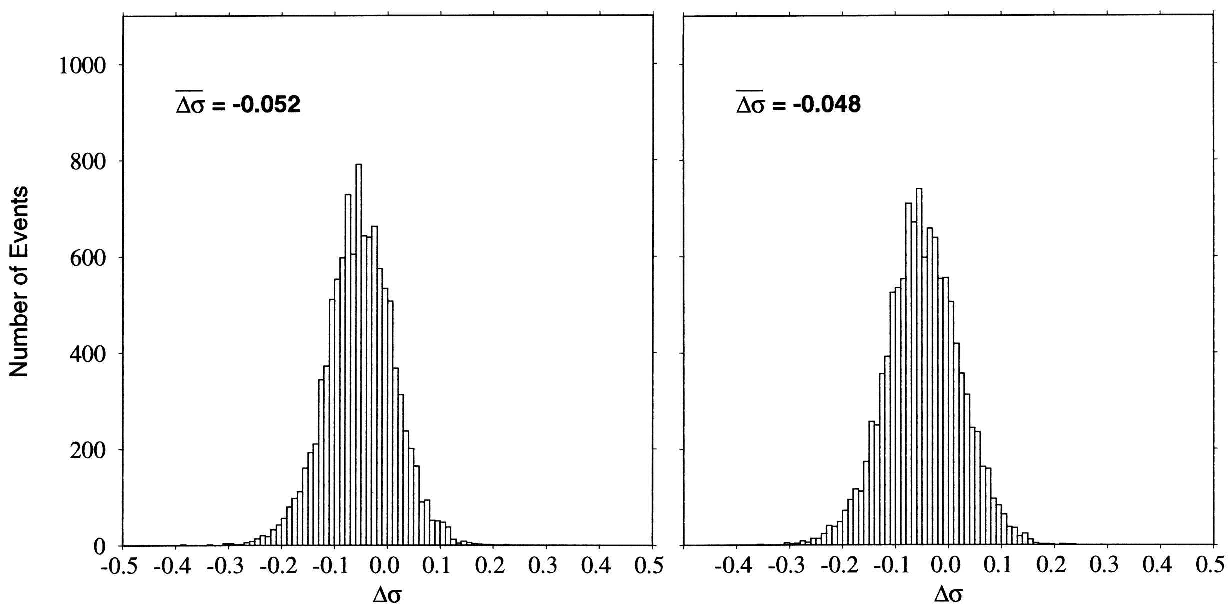


Figure 3. Comparison of the observed reductions in the standard errors of estimate obtained by applying the station corrections to all the single station P wave data in the distance range from 25 to 180 degrees (left) with those obtained for the distance range from 25 to 100 degrees (right).

To meet this objective, we have been conducting some preliminary studies to evaluate a regional magnitude measure, similar to the $m_b(L_g)$ scale defined by Nuttli (1973), which utilizes the amplitude level in a frequency band near 1 Hz measured in the L_g group velocity window and includes corrections for distance based on knowledge of regional L_g attenuation associated with the path-specific propagation. In an effort to broaden the usefulness of this measure, we are also investigating the possibility of measuring the L_g signals in somewhat higher frequency bands for smaller events, which may have larger signal-to-noise ratios at some of the nearer IMS stations.

Similarly to other magnitude measures, the L_g magnitude can be represented as the combination of the logarithm of the measured amplitude, correction factors to account for distance-dependence and station response, and a normalization term to provide some equivalency between scales:

$$m_b(L_g) = \text{Log } A + D(f,R) + S(f) + \text{Log } A_0 \qquad (3)$$

where

A	=	the measured L_g amplitude in a particular frequency (f) band
$D(f,R)$	=	a correction for signal attenuation with distance, which is frequency dependent
$S(f)$	=	a station correction, which may be frequency dependent
$\text{Log } A_0$	=	a magnitude normalization term

The Log A_0 term was originally selected by Nuttli to provide agreement between the L_g magnitude scale and the teleseismic m_b magnitude for central North America; however, alternative normalization schemes may be more appropriate for global applications and will be evaluated. We are also investigating a variety of methods for determining the distance correction factor, which would be expected to be strongly path dependent. One option would be to use the observations themselves to define D(f, R) in the region surrounding the individual IMS stations. However, we expect the availability of calibration data to be limited at most IMS stations; so a more indirect approach may be necessary. An alternative is to use a model-based approach to determine L_g attenuation for the source-station path from prior knowledge of L_g propagation characteristics in the region. In particular, there have been a number of studies (cf. Mitchell et al., 1996) covering most continental regions of the world which have determined a Q factor associated with L_g attenuation. It should be possible to use those Q values to determine the L_g attenuation and related distance corrections for the regions around IMS stations. Thus, the correction for L_g amplitude distance dependence can be expressed as the combination of geometric spreading and frequency-dependent attenuation:

$$C_R = \left(\frac{R}{R_N}\right)^{0.833} e^{\pi f \frac{(R - R_N)}{Q v}} \qquad (4)$$

where

R	=	event/station distance
R_N	=	a reference distance for normalization
Q	=	quality factor associated with regional L_g attenuation
v	=	L_g group velocity

and then the magnitude distance correction factor for L_g is just:

$$D(f,R) = \text{Log } C_R \qquad (5)$$

To test the effectiveness of the procedures, we have begun to apply this scheme to the L_g signals at selected IMS stations for events in the REB database at the PIDC during the time period 1995 – Present. For our initial work, we sought a station which had a large number of L_g observations reported for events covering a fairly large range of regional distances. We selected the IMS primary station CMAR in Thailand, for which L_g observations were reported from 240 events (cf. Figure 4). We have retrieved the broadband, vertical-component records at CMAR for these events, as well as some other larger well-recorded events to supplement the CMAR database and provide more uniform coverage over the distance range from 2 to 20 degrees (cf. Figure 5). Each broadband record was filtered using third-order Butterworth filters for several frequency bands including 0.75-1.25 Hz, 1-2 Hz, 2-4 Hz, and others. For each filtered record, amplitude measurements are being made in the L_g group velocity window (from 3.7 km/sec to 2.8 km/sec). We have been measuring peak and RMS averages of the amplitudes over the L_g window, as well as testing a few alternative measures of signal level.

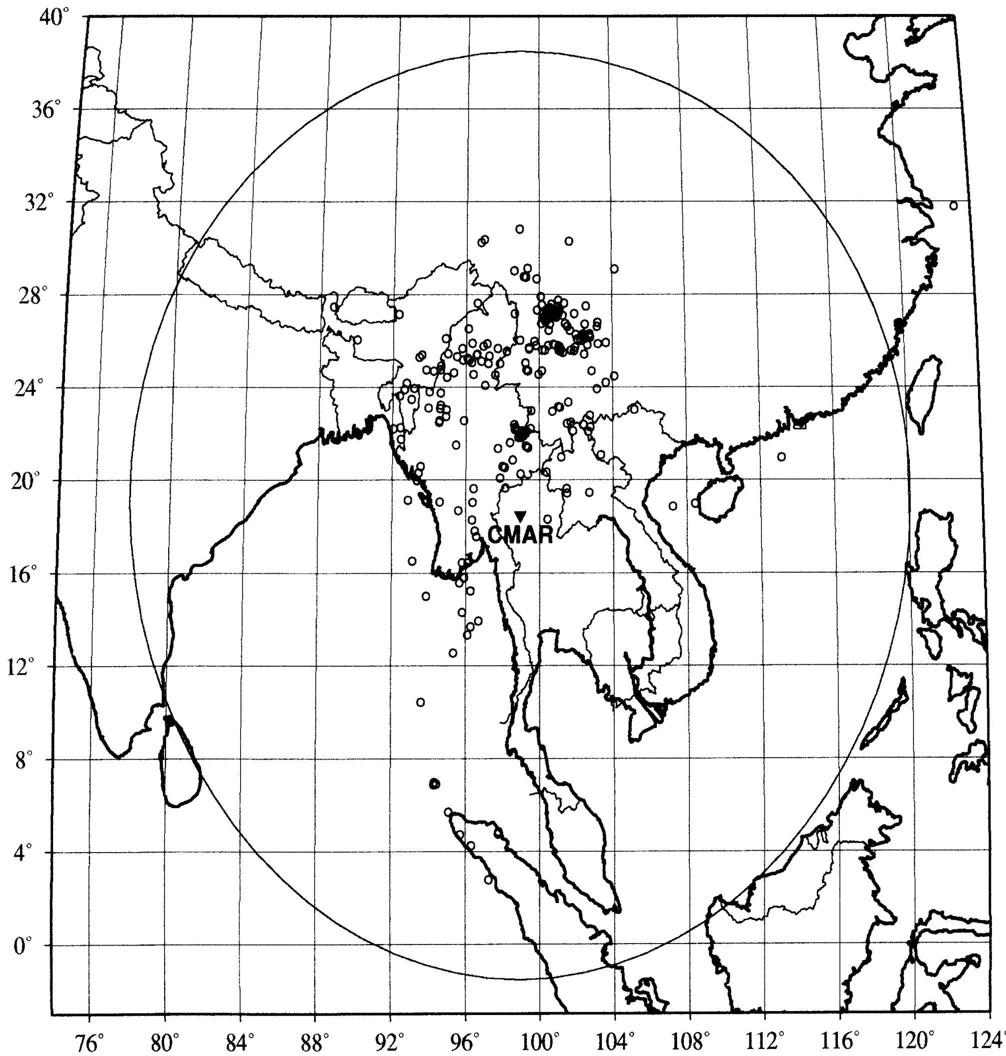
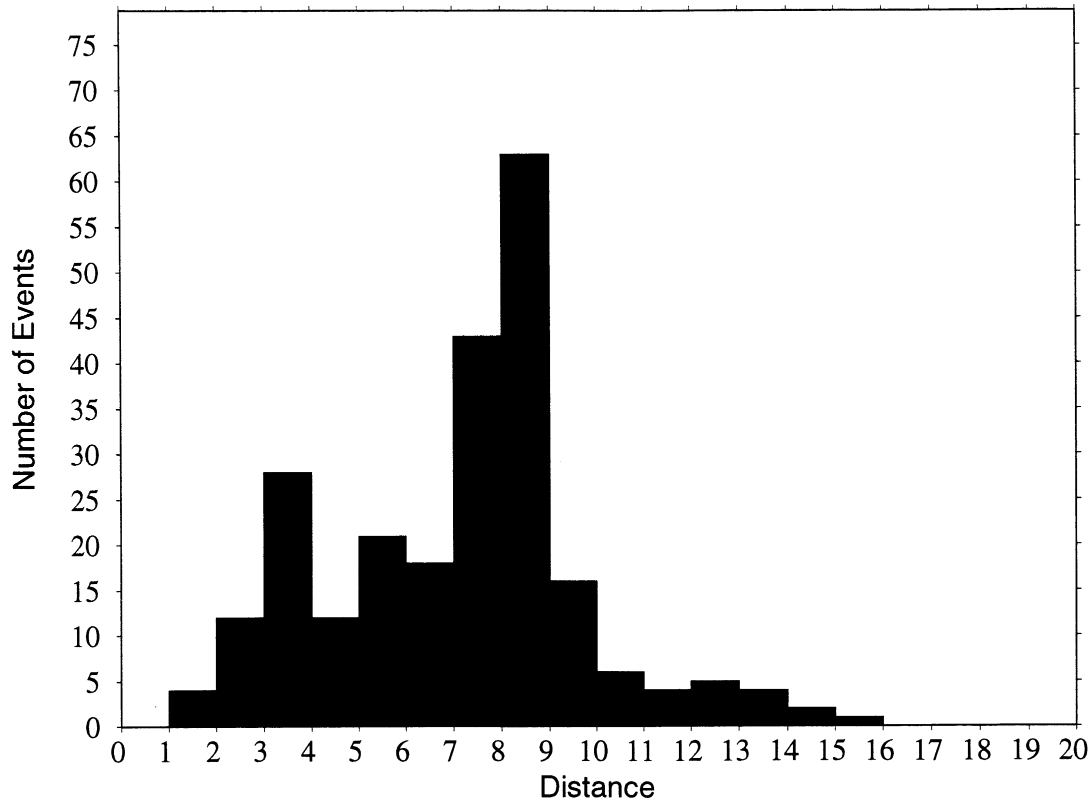


Figure 4. Locations of 242 regional events from the PIDC REB database (1995 – Present) for which Lg signals were reported at the Primary IMS station CMAR in Thailand. Large circle is at 20° from CMAR.



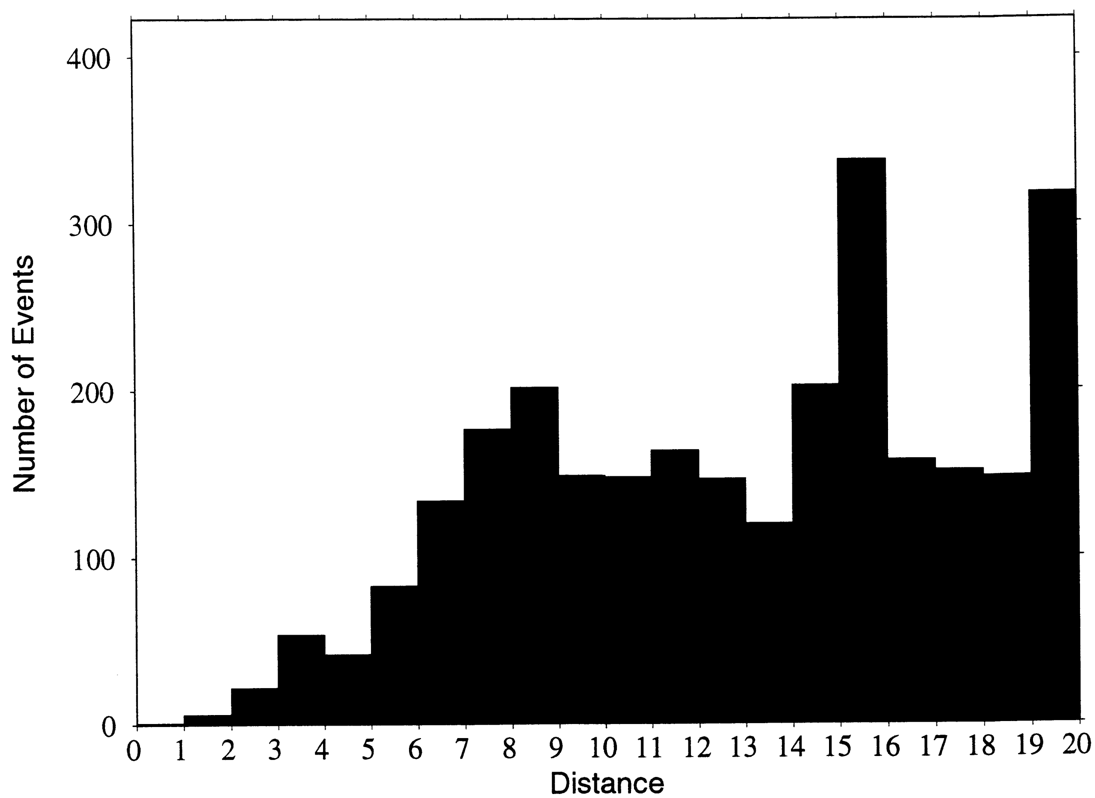


Figure 5. Distributions with respect to epicentral distance of the regional events with Lg signals reported at CMAR (top) and a large sample of 2767 REB events within 20° of CMAR (bottom) from which supplemental data have been selected.

We performed some preliminary analyses on a sample of the measurements at CMAR to determine its consistency with the attenuation model described above. For the limited sample, we found from a multivariate regression analysis that the observations for the 0.75-1.25 Hz passband could be described by a $Q_0 \approx 250$ (i.e. Q at 1 Hz) with a geometric spreading dependence of $R^{-0.83}$. This attenuation appears to be in fairly good agreement with Q_0 results reported by Mitchell et al. (1996) for L_g attenuation in this region; although those studies indicate variation in Q across the region surrounding CMAR, which would imply azimuthal dependence of the L_g magnitude distance correction.

To assess the significance of the azimuthal variations in attenuation and the utility of prior knowledge of L_g attenuation for these kinds of magnitude corrections, we have developed a procedure to determine the total L_g attenuation by summing the effects of Q along the L_g propagation path for a model in which the attenuation varies (e.g. the model of Mitchell et al.). Figure 6 shows the L_g magnitude distance correction term at 1 Hz, combining the effects of the Q model and geometrical spreading, for the region surrounding station CMAR. Although the magnitude correction term appears to be fairly symmetric, there are actually some significant differences at fixed distance as a function of azimuth which are attributable to the Q variations. As would be expected, these are most notable at larger distances where the magnitude correction changes by more than 0.5 magnitude units for events at a distance of 20 degrees over an azimuthal range of about 90 degrees around CMAR. Considering the relatively uniform behavior of the Q model around CMAR compared to some other areas, it seems likely that stronger variations in the L_g magnitude distance corrections should be expected around other IMS stations. These will need to be accounted for in developing reliable L_g magnitude measures for use at the IDC.

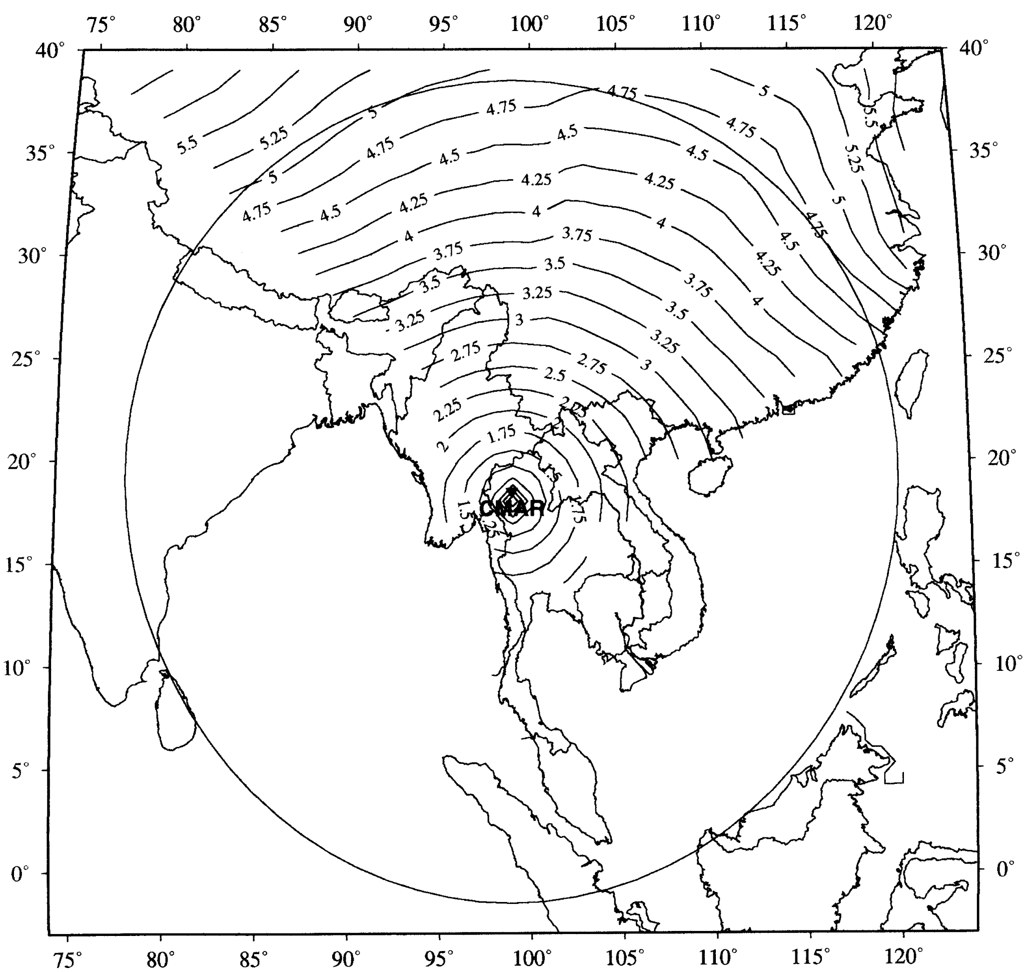


Figure 6. Contour map of Lg magnitude distance correction at 1 Hz predicted for the region surrounding CMAR by combining the effects of geometrical spreading and attenuation based on the regional Q model. Circle is at 20° from CMAR.

Surface Wave Processing – Another element of this project has been the development of improved surface wave processing for M_S magnitude determination at the IDC. A major part of this task has been to provide development and support for automatic surface wave processing using Maxwell's Maxsurf program code. This code has in fact been in place at the PIDC for several years and continues to perform well. We are in the process of completing standard documentation of the software for Maxsurf. In addition, we have developed maximum likelihood M_S station corrections for all available IMS stations, and those are now being used as part of the surface wave magnitude determinations.

CONCLUSIONS AND RECOMMENDATIONS

Significant improvements have been made in magnitude estimation procedures for use at the IDC. Procedures to enhance generalized m_b by incorporating PKP observations have been established and calibrated, and P-wave magnitudes can now be determined over the distance range from 2 to 180 degrees. m_b station corrections for use over the entire range of P wave observations have been developed. Preliminary investigations have been conducted to provide the basis for more traditional regional magnitude measures at the IDC based on L_g observations. Additional studies are needed to establish L_g magnitude distance corrections in the vicinity of IMS stations and to provide the bases for L_g magnitude calibration. Maxsurf has been established as a reliable tool for automatic surface wave processing and M_S estimation. Appropriate M_S station corrections have been determined for use with IMS stations, and these will be refined as new stations become available.

Key Words: seismic, magnitude, PKP, L_g, IDC

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